Parameter Identification for X-31A at High Angles of Attack

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The U.S./German experimental aircraft X-31A was designed and constructed to demonstrate enhanced fighter maneuverability. Post-stall maneuvering is enabled by applying new technologies such as high angle of attack aerodynamics and flight control system integrated thrust vectoring.

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Two demonstrator aircraft have been built by the main contractors Rockwell International and Deutsche Aerospace (formerly MBB). Flight testing started in October 1990 and before the end of 1992 both aircraft had accomplished a significant number of flights covering the entire AoA regime from about -5 to 70 deg.

Throughout the envelope expansion, DLR Institute of Flight Mechanics conducted parameter identification (PID) to determine the aerodynamic parameters of the aircraft from flight test data and to compare the results to the predictions from the aerodynamic dataset (ADS).

The application of system identification to high AoA / post-stall flight data raises some major problems, which are discussed in this paper. Results from both longitudinal and lateral-directional motion will be presented.

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Parameter Identification for X-31A
at High Angles of Attack

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Overview

The presentation will start with a description of the problems arising when applying parameter identification to high AoA fligh test data. Possible approaches for solving or circumventing the different problems are discussed.

The problems are further illustrated with examples from longitudinal and lateral-directional motion identification. The different identification approaches are discussed and selected results are presented.

At the end, an outlook for the upcoming identification activities will be given.

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Overview

- Problems of Identification at High Angles of Attack
- Lateral-Directional Motion
  - Instability and Process Noise
  - Insufficient Aircraft Excitation for PID
  - Aero-Update based on PID Results
- Longitudinal Motion
  - Thrust and Weight
  - Correlations
  - Influence of Aft Strakes
- Outlook

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Problems of Identification at High Angles of Attack

The identification of aerodynamic parameters from high AoA / post-stall data is made more difficult due to the following facts:

The basic (uncontrolled) aircraft is unstable. This instability leads to divergence of the system solutions which are derived by integration of the state equations. This problem can be circumvented by application of (1) estimation methods that stabilize the solutions (e.g. output error method with artificial stabilization, filter error method, and Extended Kalman Filter method) or (2) estimation algorithms which avoid integration of the state equations (regression method or frequency domain methods).

The aircraft states and controls are highly correlated. This leads to high correlations in the corresponding stability and control derivatives, such that not all derivatives can be estimated independently. Therefore, only a reduced model is identifiable, i.e. some derivatives are fixed on their predictions and/or two correlated derivatives are combined in one common parameter. The correlation problem would be overcome by single effector excitation.

The aircraft motion is disturbed by process noise induced e.g. by forebody vortices. Filter error method, Extended Kalman Filter and regression account for process noise and are therefore suitable for parameter estimation at high angles of attack.

The aircraft motion is often not sufficiently excited for PID because the (excellent) flight control system suppresses all undesired motion, e.g. sideslip is kept close to zero.

Thrust, weight and CG location are not known with sufficient accuracy.

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Problems of Identification at High Angles-of-Attack

- Instability of the Basic Aircraft
- Correlation of Aircraft States and Controls
- Process Noise
- Insufficient Aircraft Excitation for PID
- Thrust, Weight, CG Location not Known Exactly

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Instability and Process Noise

The figures show a bank-to-bank maneuver at 54 deg AoA. Parameter estimation was first carried out by using the ML output error method with artificial stabilization (left). As the stabilization affects the parameter estimates, it was reduced step by step to zero. This, however, led again to stability problems such that only part of the complete bank-to-bank maneuver could be evaluated and the shorter maneuver had to be split into two time segments, each requiring estimation of initial values of the state variables.

It can be seen that particularly the roll rate p is corrupted by process noise which cannot be modeled by the output error method. The roll rate has considerable influence on the sideslip angle β. (The ADS predictions indicate that the sideforce due to roll rate is important and must not be neglected as is usually done for conventional aircraft.) Consequently, also the sideslip angle β cannot be modeled correctly. To make this evident, the roll rate p was treated in a second step as input variable. The right figure shows that thereby a better match between measured and calculated sideslip angle could be achieved. Also the fit in the yaw acceleration has been improved.

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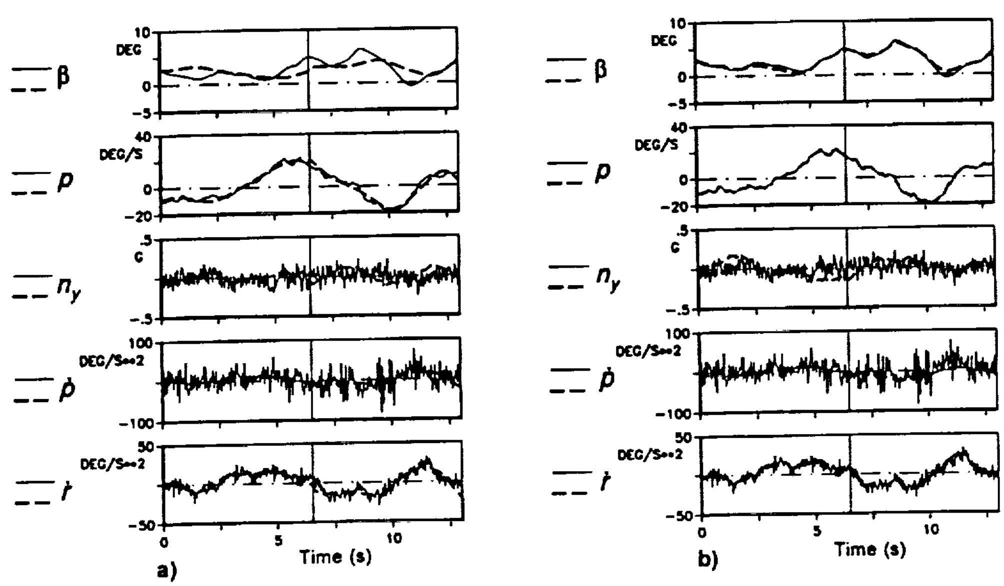
Instability and Process Noise (1)



Identification Using ML Output Error Method

a) p as state variable, b) p as input

—— flight test data, - - - model output

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These considerations show the necessity for application of estimation methods which account for process noise. As already mentioned, regression and filter error method are suitable. Both methods also overcome the problem related to the system instability. Regression requires the observation variables to be linear in the parameters. This applies to the aerodynamic coefficients C_Y, C_l and C_n. Though they are not directly measured, they can easily be computed from other measurements, essentially from the linear and angular accelerations.

The figures show the complete bank-to-bank maneuver evaluated by regression (left) and ML filter error method (right). The fit between flight test data and model output is perfect for all variables. The match in lateral, roll and yaw accelerations is of the same quality as the match in the corresponding aerodynamic coefficients obtained from regression.

The left figure also shows the correlation between differential trailing edge flap deflection δ_a and horizontal thrust deflection κ. The rudder deflection δ_r is zero, because rudder use is faded out by the flight control laws above 40 deg AoA.

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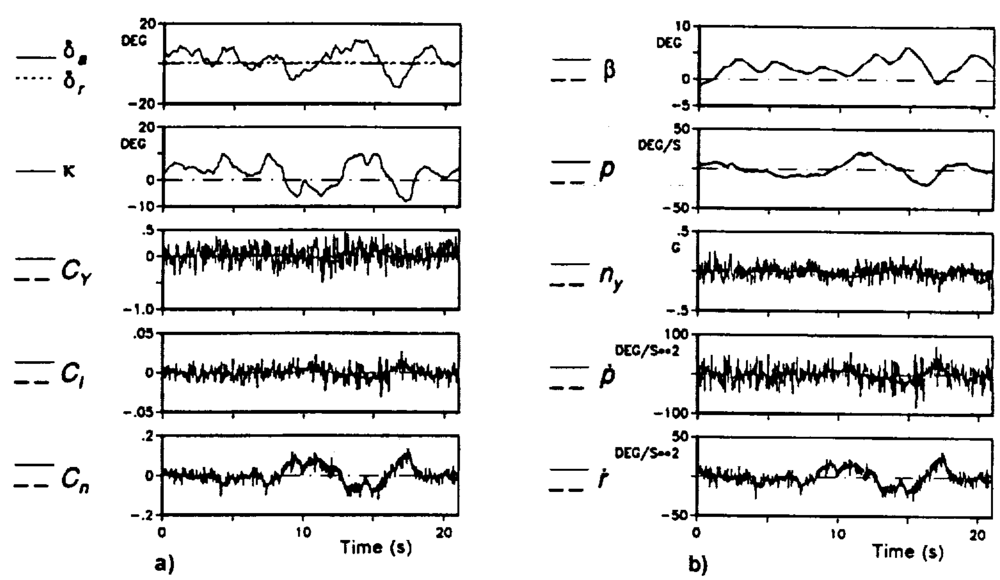
Instability and Process Noise (2)



Identification Accounting for Process Noise
a) Regression, b) ML Filter Error Method
— flight test data, - - - model output

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Insufficient Aircraft Excitation for PID

The overall low quality of the estimation results is attributed to the fact that the aircraft motion is insufficiently excited. The flight control system suppresses (as it should) all undesired motion, e.g. sideslip is kept close to zero and consequently the lateral acceleration is hardly excited. Also, the flight control system introduces artifical damping to the unstable aircraft.

That the overall information contents of the flight test data does not allow for the estimation of all aircraft parameters can be seen by the following identification results obtained using an Extended Kalman Filter algorithm (EKF). The EKF treats the aircraft parameters as additional state variables, which are assumed to be constant and are estimated together with the aircraft states.

The figure shows that some of the derivatives, like $C_{l\beta}$ and $C_{l\delta a}$ and the combined yaw damping C_{nr}^* (yawing moment due to roll and yaw rate) converge quickly whereas other parameters, such as the sideforce derivatives $C_{Y\beta}$ and $C_{Y\delta a}$ and the combined roll damping C_{lp}^*, remain with large error bounds.

Effective excitation at high AoA is prevented by the X-31A flight control laws and would be achieved only by separate excitation of the different aerodynamic control surfaces and the thrust vectoring system.

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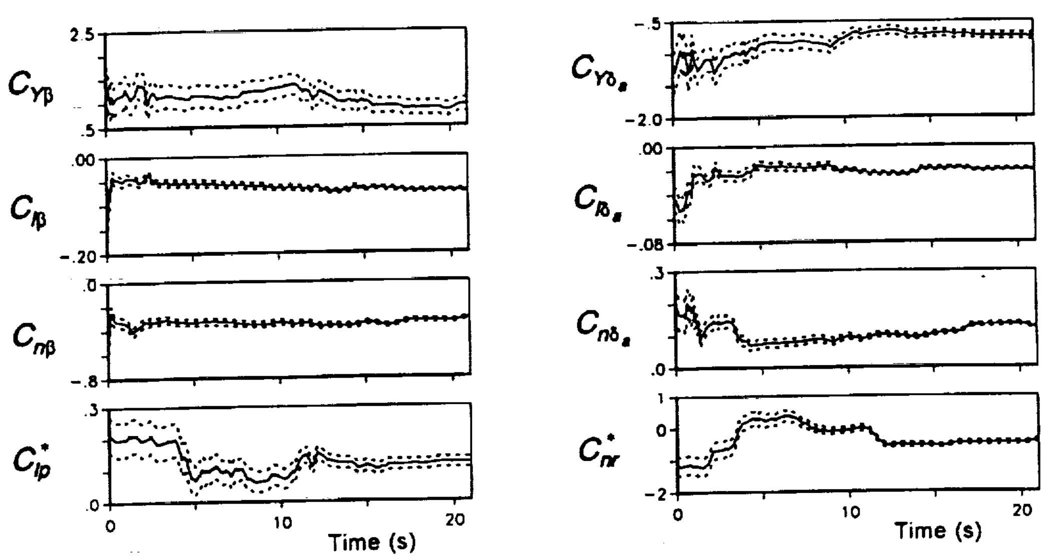
Insufficient Aircraft Excitation for PID



Identification Using Extended Kalman Filter
—— parameter value, - - - error bounds

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Aero-Update based on PID Results

Even though the quality of the parameter identification results suffers from the aforementioned difficulties, some significant deviations from the wind tunnel predictions could be identified. The figure shows the dihedral coefficient as an example. The parameter identification results did not confirm the large negative values predicted by the wind tunnel for angles of attack between 30 and 40 deg.

At the beginning of 1992, the aerodynamic database of the X-31 was updated for angles of attack up to 50 deg and the dihedral coefficient was one of the parameters that had to be changed. Identification results obtained for angles of attack above 50 deg indicate that an update of $C_{l\beta}$ in this area would also be appropriate.

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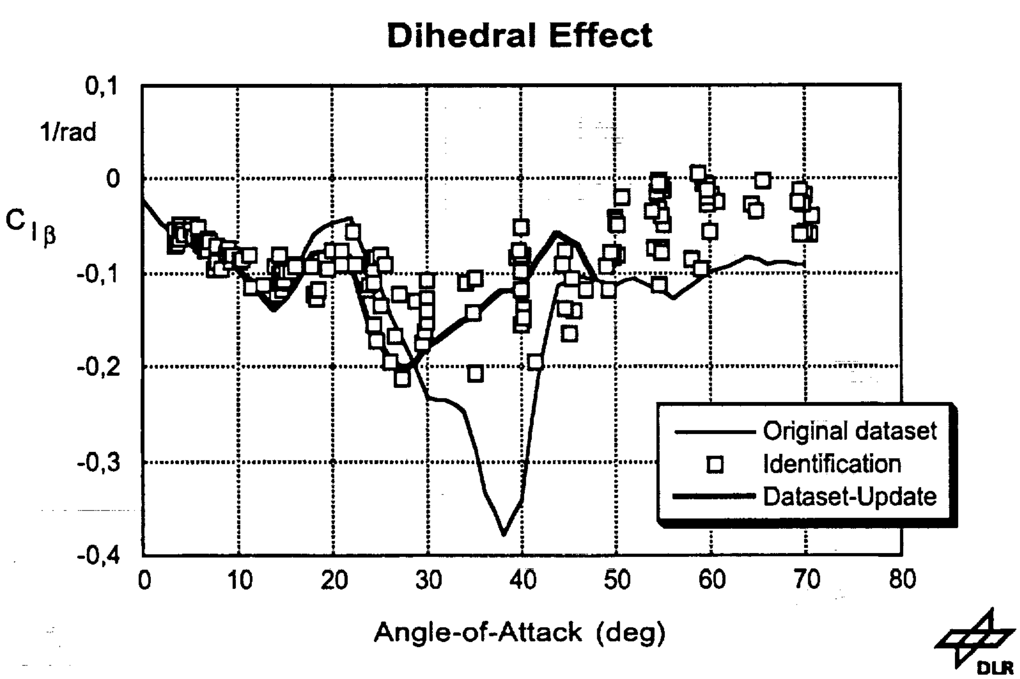
Aero-Update based on PID Results



Thrust and Weight

Especially for the longitudinal motion, an accurate knowledge of thrust, weight and CG location is crucial to obtain correct identification results. The figures below show the drag and lift coefficients, C_D and C_L, obtained by using (1) the thrust model used in the DASA simulation and (2) the thrust estimator currently implemented in the flight control laws. There are pronounced differences in the results for angles of attack above 45 deg.

Using the simulation thrust yields lift coefficients that are close to the predictions but drag coefficients that are much larger than the ADS values. With the estimated thrust, both lift and drag are somewhat higher than the predictions. This could be explained by the fuel gauge indicating too little fuel weight for high AoA (corresponding to high pitch attitude). The aircraft weight is then underestimated which in turn leads to higher drag and lift coefficients.

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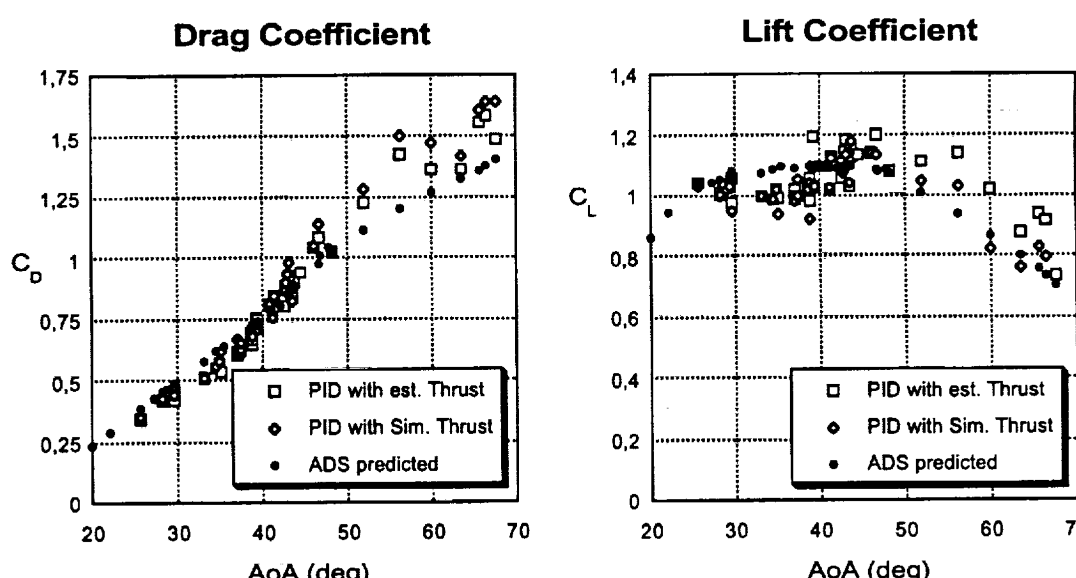
Thrust and Weight



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Correlations

As parameter identification is carried out with data from pilot generated maneuvers, control surface deflections and aircraft states are always correlated due to the flight control laws. For the lateral-directional motion, roll stick deflection commands roll around the velocity vector so that roll and yaw rate are correlated as well as aileron and horizontal thrust deflection. Therefore, the derivatives C_{Y_r}, C_{l_r} and C_{n_p} were set to zero (resulting in combined derivative estimation) and the TV effectiveness was set to a previously identified value.

In the longitudinal motion, the flight control laws lead to correlations between canard deflection δ_{can} and angle of attack α and between symmetric trailing edge deflection δ_e and vertical thrust deflection σ. This can be seen in the left figure which shows time histories from a pitch doublet at 35 deg AoA. Therefore, canard effectiveness was fixed at its predicted value for parameter identification throughout the entire AoA regime. For the post-stall regime, either trailing edge or thrust vector effectiveness had to be fixed.

The diagram on the right side shows identification results for the trailing edge flap effectiveness, obtained with thrust vectoring effectiveness as predicted. The uncertainty levels are large, especially for very high angles of attack. No influence of the aft strakes on this parameter could be identified.

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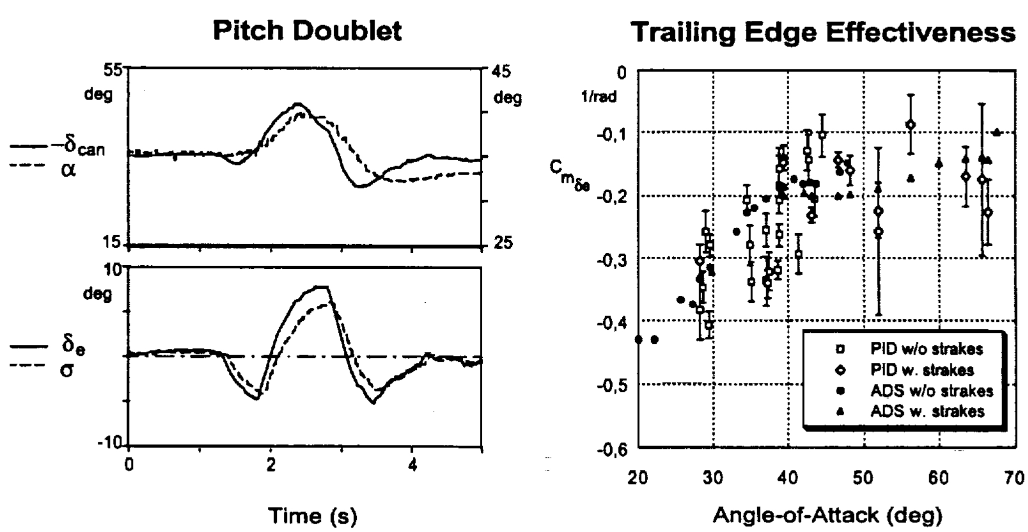
Correlations



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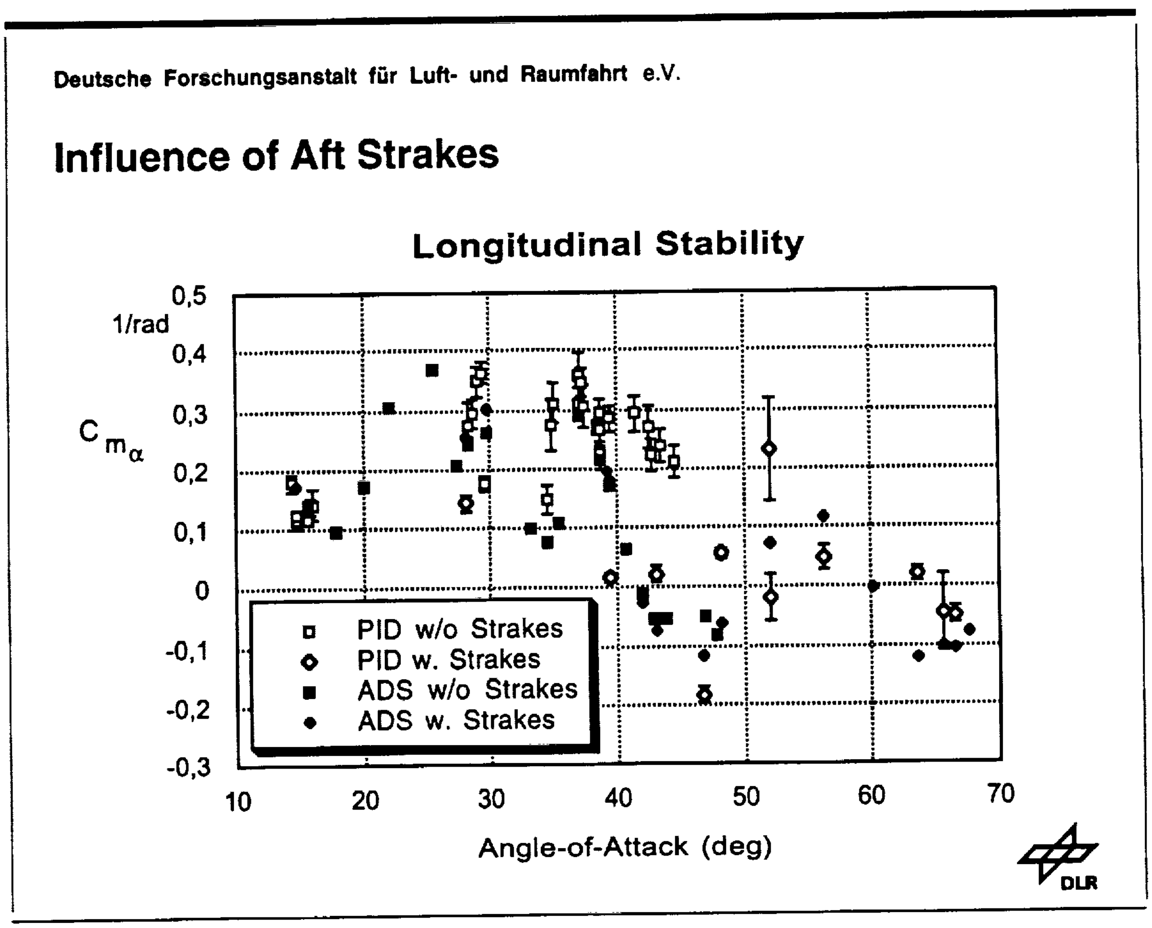
Influence of Aft Strakes

During early post-stall envelope expansion, it was discovered that the aircraft had significantly more nose up pitching moment than originally designed. The cause was found in changes made to the aft fuselage during the latter design phase. The problem was solved by installing strakes on the lower aft fuselage below the speedbrakes. The strakes brought the pitching moment sufficiently close to the original value used in the control law design.

The diagram below shows the identified values for the longitudinal stability, again obtained with canard and thrust vectoring effectiveness fixed at their predicted values. The identification results show that the trim changes caused by the aft strakes lead to increased stability as was predicted by the aerodynamic dataset.



Conclusions

X-31A parameter identification was carried out for angles of attack up to 70 deg. Aerodynamic parameters were mainly extracted from pilot generated doublet inputs and bank-to-bank maneuvers. Problems related to system instability and process noise could be overcome by the choice of appropriate estimation algorithms, e.g. regression and filter error method.

High correlations, however, allow only the identificaton of reduced aerodynamic models. Due to insufficient excitation of the aircraft motion at high AoA, the parameter estimates show large uncertainty levels and scatter.

In spite of the low quality of the estimation results, some deviations from the wind tunnel predictions could be identified in the lateral-directional axis and led to corresponding updates of the aerodynamic dataset.

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Conclusions

- PID conducted up to 70 deg AoA
- Application of
  - ML Output Error Method
  - ML Filter Error Method
  - Extended Kalman Filter
  - Regression
- Reduced Aerodynamic Models
- PID results led to Update of the ADS

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Outlook

Still in 1994, flight tests will be conducted using the flutter test box with a DLR fabricated signal generation card. This will allow single surface excitation of the aerodynamic control surfaces with inputs optimized for parameter identification. However, the thrust vectoring vanes cannot be excited directly by the flutter test box. These maneuvers should yield uncorrelated estimates for the stability and control derivatives up to 45 deg AoA.

Flight test maneuvers aimed at investigating nonlinear and unsteady effects, which were suggested by NASA Langley, have been flown.

Insight gained from both of these sets of parameter identification maneuvers will also aid in further evaluation of the data available so far.

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Outlook

- **Single Surface Excitation**
  - flight tests with DLR card
- **Modeling of Nonlinear and Unsteady Effects**
  - flight tests (suggested by NASA Langley)
- **Further Evaluation of Current Data**

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